

## A MODEL OF METALLICITY EVOLUTION IN THE EARLY UNIVERSE

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### ABSTRACT

We apply the phenomenological model used to explain the abundances of Fe and *r*-process elements in very metal-poor stars in the Galaxy to [Fe/H] of damped Ly $\alpha$  systems. It is assumed that the first stars that formed after the big bang were very massive and that they promptly enriched the interstellar medium to [Fe/H]  $\sim -3$ , at which metallicity the formation of normal stars took over. Subsequent Fe enrichment was provided by Type II supernovae. The range of [Fe/H] at a given redshift  $z$  for damped Ly $\alpha$  systems is explained by the time  $t^*$  after the big bang at which normal star formation started in an individual protogalactic system. The average  $t^*$  is  $\approx 80\%$  the age of the universe for damped Ly $\alpha$  systems at  $z \approx 1.5$ – $4.5$ , indicating a long delay between the big bang and the turn-on of protogalaxies. It is inferred that a substantial fraction of the total baryonic matter may not have been aggregated into protogalaxies with normal star formation events until a late time corresponding to  $z \sim 1.5$ . The data near  $z = 2.2$  indicate that the rate of turn-on of protogalaxies was initially very low and that it slowly reached a maximum at  $\sim 3$  Gyr after the big bang. This rate of turn-on of galaxies may be important in understanding the rate of formation of quasars.

*Subject headings:* galaxies: abundances — galaxies: evolution — quasars: absorption lines

### 1. INTRODUCTION

In a recent paper, Prochaska & Wolfe (2000) reported new data on [Fe/H] for damped Ly $\alpha$  systems at high redshifts. They also summarized available data with redshifts from  $z \approx 1.5$  to  $4.5$  (e.g., Lu et al. 1996; Lu, Sargent, & Barlow 1997; Prochaska & Wolfe 1999). Their observations are in general accord with previous studies and expand the database at  $z > 3$  substantially. Prochaska & Wolfe (2000) emphasized that there is a wide spread in [Fe/H] at a given  $z$  and that no damped Ly $\alpha$  system has [Fe/H]  $< -2.7$  (see also Lu et al. 1996, 1997). They also pointed out that there is only a minimal growth of [Fe/H] from  $z \approx 4.5$  to  $1.5$ . In a theoretical study of Fe and *r*-process abundances in very metal-poor stars in the Galaxy by Wasserburg & Qian (2000, hereafter WQ), it was proposed that the first stars that formed after the big bang were very massive ( $\geq 100 M_\odot$ ) and that they promptly enriched the interstellar medium (ISM) to [Fe/H]  $\sim -3$ , at which metallicity the formation of normal stars (with masses  $\sim 1$ – $60 M_\odot$ ) took over. Subsequent Fe enrichment was provided by a subset of Type II supernovae. The interpretations of WQ were based on observations of metal-poor stars in the Galaxy by Gratton & Sneden (1994), McWilliam et al. (1995), McWilliam (1998), and Sneden et al. (1996, 1998). The apparent agreement between the lower bound on [Fe/H] of damped Ly $\alpha$  systems and the critical metallicity [Fe/H]  $\sim -3$  deduced by WQ for the transition from the formation of very massive stars to normal stars suggests that this Fe-enrichment model deserves further study.

Here we present a phenomenological model for the range of [Fe/H] at a given  $z$  for damped Ly $\alpha$  systems based on the model of WQ. It is assumed that the formation of normal stars started in a damped Ly $\alpha$  system (i.e., a protogalactic system turned on) at a time  $t^*$  after the big bang. The assembly of [Fe/H] at a given  $z$  is interpreted as a sampling of  $t^*$  ranging from 0 to the age of the universe at  $z$ ,  $t(z)$ . The value  $t^* \sim 0$  corresponds to the upper bound on [Fe/H]. Furthermore, the

distribution of  $t^*$  at a given  $z$  indicates the rate of turn-on of protogalaxies prior to  $t(z)$ . The data near  $z = 2.2$  suggest that this rate was initially very low and that it slowly reached a maximum at  $\sim 3$  Gyr after the big bang. We describe the Fe-enrichment model in detail in § 2 and apply it to explain the data on [Fe/H] of damped Ly $\alpha$  systems in § 3. Discussion and conclusions are given in § 4.

### 2. Fe ENRICHMENT AND ABUNDANCES IN METAL-POOR STARS

The Fe-enrichment model of WQ was developed to explain the relation between abundances of Fe and *r*-process elements (*r*-elements) in metal-poor stars in the Galaxy. Meteoritic data on the inventory of radioactive  $^{129}\text{I}$  and  $^{182}\text{Hf}$  in the early solar system require at least two distinct Type II supernova sources for the *r*-process (Wasserburg, Busso, & Gallino 1996; Qian, Vogel, & Wasserburg 1998; Qian & Wasserburg 2000). These are the high-frequency H events responsible for heavy *r*-elements with mass numbers  $A > 130$  (e.g., Ba and Eu) and the low-frequency L events responsible for light *r*-elements with  $A \leq 130$  (e.g., Ag). The recurrence timescales for the H and L events are  $\Delta_H \approx 10^7$  yr and  $\Delta_L \approx 10^8$  yr, respectively, as required by replenishment of the appropriate radioactive nuclei in a standard mixing mass (approximately the size of a molecular cloud) for a supernova. Additional evidence in support of different sources for the heavy and light *r*-elements has been found by Sneden et al. (2000).

The observed wide dispersion in abundances of the heavy *r*-elements such as Ba and Eu over a narrow range of [Fe/H]  $\sim -3$  to  $-2.8$  (McWilliam et al. 1995; McWilliam 1998; Sneden et al. 1996, 1998) led WQ to conclude that the H events cannot produce a significant amount of Fe. In contrast, there is a correlation between abundances of Fe and the heavy *r*-elements at [Fe/H]  $\geq -2.5$  (Gratton & Sneden 1994; see also McWilliam et al. 1995). Since Type Ia supernovae would occur only at metallicities much higher than [Fe/H]  $= -2.5$ , the Fe enrichment of very metal-poor stars with [Fe/H]  $\geq -2.5$  must be provided by the L events. Consequently, the L events are responsible for the part of Fe contributed by Type II supernovae in general. There are  $\approx 100$  L events during the time of  $\approx 10^{10}$  yr prior to solar system formation. To provide  $\approx \frac{1}{3}$  of the

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solar Fe inventory by these events, each L event must enrich a standard mixing mass with  $[\text{Fe}/\text{H}]_{\text{L}} \approx -2.5$ .

The near absence of the heavy  $r$ -elements in stars with  $[\text{Fe}/\text{H}] \sim -4$  to  $-3$  (McWilliam et al. 1995; McWilliam 1998) and the sharp increase in the abundances of such elements at  $[\text{Fe}/\text{H}] \sim -3$  to  $-2.8$  led WQ to conclude that a source other than Type II supernovae must exist to produce Fe (along with other elements such as C, N, O, Mg, and Si) at  $[\text{Fe}/\text{H}] \leq -3$ . This source was attributed by WQ to very massive stars (with masses  $\geq 100 M_{\odot}$ ) that first formed after the big bang. They further argued that the formation of normal stars could not occur until  $[\text{Fe}/\text{H}] \sim -3$  was reached. Presumably, this critical metallicity corresponds to conditions in the ISM that permit sufficient cooling and fragmentation to occur in collapsing gas clouds. A recent study by Bromm, Coppi, & Larson (1999) suggests that the very first stars were rather massive. The products of very massive stars that formed from big bang debris have been discussed earlier by Ezer & Cameron (1971). However, nucleosynthesis in such stars remains to be tested with adequate stellar models.

### 3. $[\text{Fe}/\text{H}]$ OF DAMPED $\text{Ly}\alpha$ SYSTEMS

To discuss  $[\text{Fe}/\text{H}]$  of a damped  $\text{Ly}\alpha$  system at a given  $z$ , we assume the following history for its evolution: (1) at time  $t_1$  after the big bang, matter consisting of big bang debris was isolated to form a system; (2) “prompt” enrichment by the first very massive stars ended at time  $t_2$ , resulting in  $[\text{Fe}/\text{H}] \sim -3$  in the ISM; and (3) the formation of normal stars began at time  $t^*$ , with the L events providing further Fe enrichment to an average ISM at regular intervals. The above times are related as  $t_1 < t_2 < t^*$ . Since  $t^* \leq t(z)$ , it is necessary to define the value of  $t(z)$  that is used. We take the redshift  $z$  to correspond to a time

$$t(z) \approx \frac{2}{3} H_0^{-1} \Omega_m^{-1/2} (1+z)^{-3/2} \quad (1)$$

after the big bang. We take the Hubble constant  $H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$  and the matter contribution to the critical density  $\Omega_m = 0.3$  [eq. (1) gives essentially the exact result for  $t(z)$  at  $z \geq 1.5$  for a flat universe with  $\Omega_m = 0.3$  and a cosmological constant]. By our assumption, for  $t(z) \geq t_2$ , the metallicity of a damped  $\text{Ly}\alpha$  system is at least  $[\text{Fe}/\text{H}] \sim -3$ . Prochaska & Wolfe (2000) reported that no system at  $z \approx 1.5$ – $4.5$  has  $[\text{Fe}/\text{H}] < -2.7$ . This means that the time required to provide prompt Fe enrichment must be less than  $t(z \approx 4.5) \approx 1.4 \text{ Gyr}$ . The lower bound on  $[\text{Fe}/\text{H}]$  due to prompt enrichment is shown as a band between  $-3$  and  $-2.8$  in Figure 1 together with the data summarized in Prochaska & Wolfe (2000).

In general, for  $t(z) \geq t^*$ , the metallicity of a specific damped  $\text{Ly}\alpha$  system at  $z$  is given by

$$(\text{Fe}/\text{H}) = (\text{Fe}/\text{H})_p + (\text{Fe}/\text{H})_{\text{L}} \frac{t(z) - t^*}{\Delta_{\text{L}}}, \quad (2)$$

where the number ratio in parentheses  $(\text{Fe}/\text{H})$  is related to the standard bracket notation by  $[\text{Fe}/\text{H}] = \log (\text{Fe}/\text{H}) - \log (\text{Fe}/\text{H})_{\odot}$ , with  $(\text{Fe}/\text{H})_p$  corresponding to the prompt enrichment and  $(\text{Fe}/\text{H})_{\text{L}}$  to the contribution from a single L event to a standard reference mass of hydrogen. We take  $[\text{Fe}/\text{H}]_p = -2.8$ ,  $[\text{Fe}/\text{H}]_{\text{L}} = -2.5$ , and  $\Delta_{\text{L}} = 10^8 \text{ yr}$ , which are the same parameters used by WQ. As recognized by Lu et al. (1996), the scatter in  $[\text{Fe}/\text{H}]$  at a given  $z$  for damped  $\text{Ly}\alpha$  systems might result from

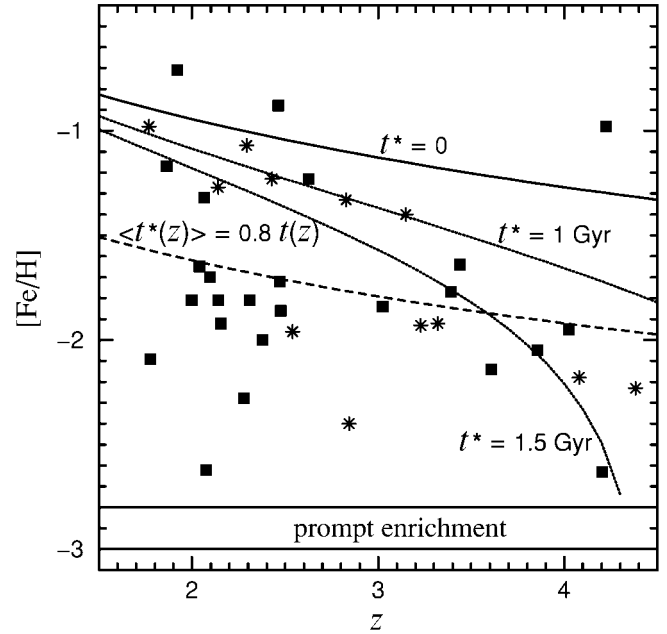


FIG. 1.—Summary of the available data on  $[\text{Fe}/\text{H}]$  of damped  $\text{Ly}\alpha$  systems at  $z \approx 1.5$ – $4.5$  (asterisks: Lu et al. 1996, 1997; squares: Prochaska & Wolfe 1999, 2000). The curve labeled  $t^* = 0$  is the upper bound from eq. (2) with  $[\text{Fe}/\text{H}]_p = -2.8$ ,  $[\text{Fe}/\text{H}]_{\text{L}} = -2.5$ , and  $\Delta_{\text{L}} = 10^8 \text{ yr}$ . The curve labeled  $\langle t^*(z) \rangle = 0.8 t(z)$  appears to represent the average trend of the data. Curves for  $[\text{Fe}/\text{H}]$  corresponding to fixed values of  $t^* = 1$  and  $1.5 \text{ Gyr}$  are also shown.

their different formation histories. Equation (2) explicitly states that the range of  $[\text{Fe}/\text{H}]$  at  $z$  is caused by the different start times  $t^*$  for normal star formation in individual systems (see Fig. 2a). The values for  $[\text{Fe}/\text{H}]$  corresponding to  $t^* = 1$  and  $1.5 \text{ Gyr}$  are shown in Figure 1. Damped  $\text{Ly}\alpha$  systems that just turned on at  $t^* \approx t(z)$  would have  $[\text{Fe}/\text{H}] \approx [\text{Fe}/\text{H}]_p$ . An upper bound on  $[\text{Fe}/\text{H}]$  exists as damped  $\text{Ly}\alpha$  systems that turned on at  $t^* \sim 0$  would have the longest history of normal star formation and hence the highest  $[\text{Fe}/\text{H}]$ . This bound is insensitive to the choice of  $[\text{Fe}/\text{H}]_p$ . It can be seen from Figure 1 that almost all the data lie below the upper bound (usually well below this bound). Even the three exceptions are close to this bound (see § 4).

At a fixed  $z$ , equation (2) with equation (1) can be used to determine the start time  $t^*$  for normal star formation in a damped  $\text{Ly}\alpha$  system from its  $[\text{Fe}/\text{H}]$ . In turn, a histogram of the number of systems at  $z$  within a given  $[\text{Fe}/\text{H}]$  interval determines the probability  $p(t^*, t(z)) dt^*$  for normal star formation to start in the interval between  $t^*$  and  $t^* + dt^*$  after the big bang. Knowing the probability distribution  $p(t^*, t(z))$  over  $0 < t^* \leq t(z)$  at  $z$ , we expect that the probability distribution at  $z' > z$  can be obtained by discarding the part of  $p(t^*, t(z))$  for  $t^* > t(z')$  and renormalizing the remaining part over  $0 < t^* \leq t(z')$  (see Fig. 2b). For the case of a simple power-law distribution,  $p(t^*, t(z)) = [(\alpha + 1)/t(z)][t^*/t(z)]^\alpha$ . In this case, the average start time for normal star formation in damped  $\text{Ly}\alpha$  systems at  $z$  is  $\langle t^*(z) \rangle = [(\alpha + 1)/(\alpha + 2)]t(z)$ .

The data in Figure 1 show a relatively high concentration in the interval  $2.0 \leq z \leq 2.4$ . The average start time in this interval is  $\langle t^*(z = 2.2) \rangle \approx 2.5 \text{ Gyr}$ . The frequency of occurrences of  $t^*$  calculated from the data in this interval is shown as a histogram in Figure 3. It can be seen that the frequency of occurrences is low for  $t^* \sim 0$  (close to the big bang) and that it slowly increases to a maximum at  $t^* \sim 3 \text{ Gyr}$ . Assuming a power-law distribution for  $t^*$ , we obtain  $\alpha \approx 3$ , for which

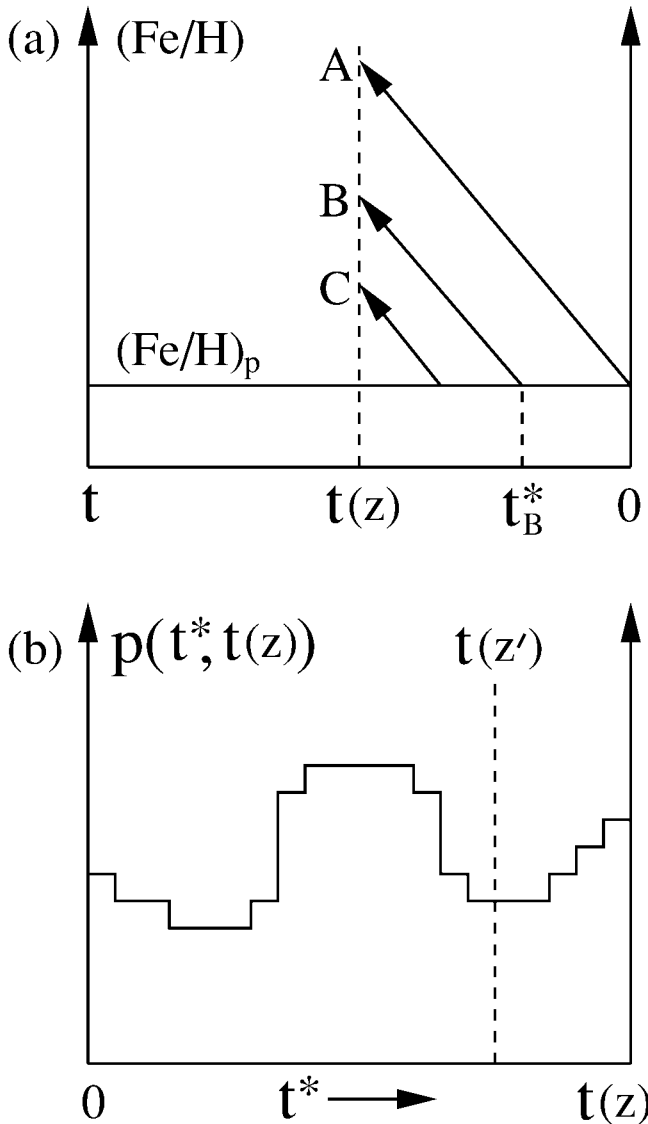


FIG. 2.—(a) Schematic diagram of  $(\text{Fe}/\text{H})$  as a function of  $t^*$  at a fixed  $z$ . The baseline  $(\text{Fe}/\text{H})_p$  is the prompt enrichment value. Normal star formation began in a protogalactic system at time  $t^*$  after the big bang. After reaching  $(\text{Fe}/\text{H})_p$ , a particular mass of matter must wait until  $t^*$  to start the increase in  $(\text{Fe}/\text{H})$  by contributions from Type II supernova L events. For  $t^* = 0$ , there is a maximum increase in  $(\text{Fe}/\text{H})$  (trajectory A). As  $t^*$  approaches  $t(z)$ , the growth is proportionally smaller (trajectories B and C). (b) Schematic histogram for the distribution of  $t^*$  in a set of damped  $\text{Ly}\alpha$  systems at a given  $z$ . The distribution for  $z' > z$  can be obtained by discarding the part of the distribution for  $z$  at  $t^* > t(z')$ .

$\langle t^*(z) \rangle \approx 0.8t(z)$  (see the corresponding curve for  $[\text{Fe}/\text{H}]$  shown in Fig. 1). Values of  $t^*$  for all the data are shown in Figure 4. The clustering of  $t^*$  close to  $t(z)$  indicates that typically there is a long delay between the big bang and the start time  $t^*$  for normal star formation in damped  $\text{Ly}\alpha$  systems.

#### 4. DISCUSSION AND CONCLUSIONS

We consider the dominant cause of dispersion of  $[\text{Fe}/\text{H}]$  at a given  $z$  for damped  $\text{Ly}\alpha$  systems to be the variation in the start time ( $t^*$ ) after the big bang for normal star formation in different protogalaxies. This approach provides a chronology relative to big bang for the turn-on of galaxies based on the production of Fe by Type II supernovae. The bounds on

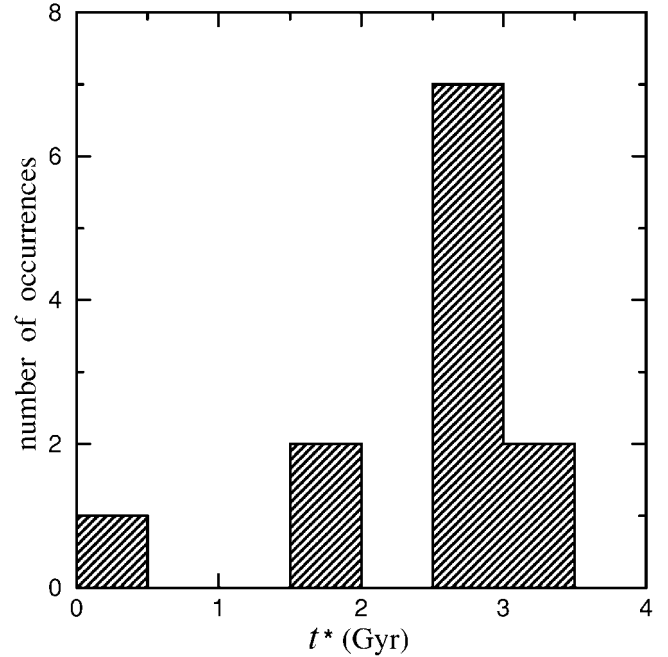


FIG. 3.—Histogram of  $t^*$  for data in the range  $2.0 \leq z \leq 2.4$  in Fig. 1 showing a peak at  $t^* \approx 2.5$  Gyr when  $t(z = 2.2) \approx 3.2$  Gyr. This shows that the rate of turn-on of protogalaxies starts from a low value close to the big bang and increases until at least  $z \approx 2$ .

$[\text{Fe}/\text{H}]$  from our model appear to define closely the observed ranges. The average  $t^*$  for damped  $\text{Ly}\alpha$  systems at  $z$  is  $\langle t^*(z) \rangle \approx 0.8t(z)$ . The rate of turn-on of protogalaxies was initially very low and slowly increased to a maximum at  $\sim 3$  Gyr after the big bang. It is not possible to identify a turnover in this rate without more data at  $z < 2$ . We suggest that the approach outlined here is a method for dating the start time for

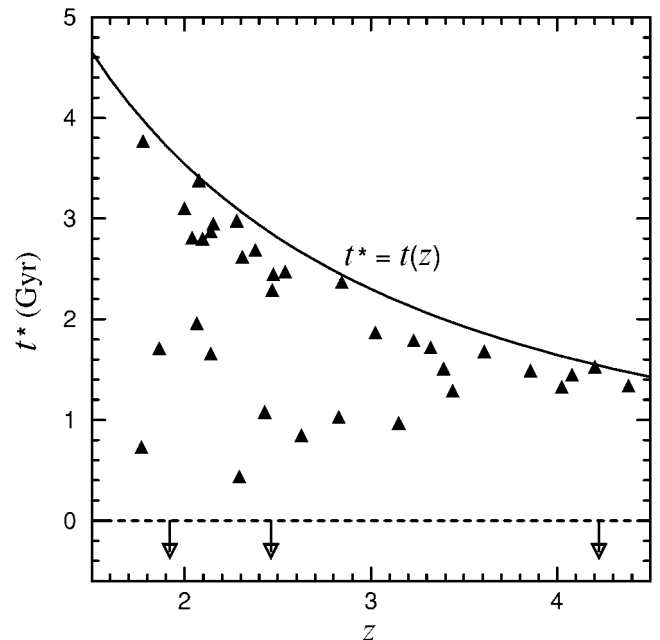


FIG. 4.—Values of  $t^*$  calculated from eq. (2) with  $[\text{Fe}/\text{H}]_p = -2.8$ ,  $[\text{Fe}/\text{H}]_L = -2.5$ , and  $\Delta_L = 10^8$  yr for all data in Fig. 1. Note the clustering of  $t^*$  close to  $t(z)$  over the range of  $z$ . Three data points indicated by downward arrows require  $t^* < 0$ .

normal star formation in protogalaxies. Since the formation of quasars is closely related to formation of active protogalaxies, we consider that the histogram shown in Figure 3 may offer some insights into the rate of formation of quasars. For example, if the rate of quasar formation  $R_Q$  is proportional to the turn-on rate of protogalaxies, Figure 3 suggests that  $R_Q \propto (t^*)^3 \propto (1+z)^{-4.5}$  at  $z \gtrsim 2$ . This gives a decrease by a factor of 2.7 in  $R_Q$  from  $z = 3$  to 4, consistent with the drop in the quasar comoving space density at these redshifts (Schmidt, Schneider, & Gunn 1995).

The three data points that lie above the upper bound in Figure 1 could be explained if the enrichment rate  $\beta_L \equiv (\text{Fe}/\text{H})_L/\Delta_L$  of L events were increased by a factor of  $\sim 2$  corresponding to the Fe contribution from Type II supernovae being  $\sim \frac{2}{3}$  of the solar Fe inventory. It is possible that  $\beta_L$  has a spread of a factor of 2 or 3. Alternatively, we can consider the enrichment rate as a steep function of time, with  $\beta_L(t)$  starting quite high and then settling down to the value proposed by WQ. In this case,  $(\text{Fe}/\text{H}) = (\text{Fe}/\text{H})_p + \int_{t^*}^{t(z)} \beta_L(t') dt'$ , and the straight line evolution in Figure 2a would be replaced by a curve. We note that Fe enrichment by Type Ia supernovae would not be significant for most damped Ly $\alpha$  systems since such enrichment appears to be significant only at  $[\text{Fe}/\text{H}] > -1$  in the Galaxy (Timmes, Woosley, & Weaver 1995).

A more difficult matter is the timescale for condensing protogalactic globs during the expansion of the universe and the timing sequence outlined above. The range in  $t^*$  required is large and indicates that the time required to form protogalaxies and condense most of the baryonic matter into stars is comparable to the age of the universe at  $z \sim 2$  ( $\sim 3.5$  Gyr after the big bang) or possibly even longer. This is in conflict with *ab initio* models that report almost complete condensation of dark matter and possibly cloud or protogalaxy formation at  $z \sim 10$ –20 (e.g., Kamionkowski, Spergel, & Sugiyama 1994). The occurrence of  $[\text{Fe}/\text{H}] \approx -2.6$  at  $z \approx 2$  implies that there are regions where formation of normal stars did not begin until  $\approx 3.5$  Gyr after the big bang. The occurrence of  $[\text{Fe}/\text{H}] \approx -2.6$  to  $-2.4$  in the range of  $z \approx 2.0$ –4.2 indicates that a large fraction of the baryonic matter has not been condensed into protogalaxies and stars over the corresponding extended time range. If damped Ly $\alpha$  systems are random samples of the original medium, this indicates that the reservoir of original un-

condensed baryonic material may not have been seriously diminished over  $\sim 3.5$  Gyr. Indeed, it is possible that the bulk of this baryonic matter is dispersed and has not condensed today. Measurements of damped Ly $\alpha$  systems at lower redshifts (but at times before Type Ia supernovae contribute Fe) would provide a test. We have no means of establishing a priori whether the intrinsic rate of protogalaxy formation decreases with time (possibly because of decrease in global density) without appreciably depleting the reservoir of baryonic matter.

A variant of the above scenario is possible that would not be in conflict with the models that suggest almost complete condensation of baryonic matter by  $z \sim 10$ . The modified scenario would be that most baryonic matter in the potential well created by nonbaryonic dark matter is rapidly collected into Ur-protogalaxies, that the formation of very massive stars from big bang debris is rapid [ $t_2 \ll t(z)$ ], and that the explosion of these very massive stars destroys the Ur-protogalaxies and re-distributes matter into the general medium, providing a uniform source of Fe (and other elements such as C, N, O, Mg, and Si). The material in this second-generation medium is then the source for a much slower aggregation and formation of protogalaxies and stars. The explosion of very massive stars is likely to be very energetic. The potential wells formed by dark matter are considered to have a typical escape velocity of  $\sim 400 \text{ km s}^{-1}$ . The velocity of debris ejected from the explosion of very massive stars is almost certainly much larger than this value. The inter-protogalactic medium would then be supplied with hot matter containing Fe, Si, Mg, O, and C. A hint in favor of this is found in the recent detection of O VI quasar absorption systems at low redshifts (Tripp, Savage, & Jenkins 2000). Knowledge of the explosion dynamics and the nucleosynthetic products of very massive stars formed from big bang debris is fundamental to further progress.

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